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14. ABSTRACT
We have fabricated electrically pumped, semiconductor TBR lasers in the InP/InGaAsP material system to demonstrate the efficiency gains possible by the incorporation of a transverse Bragg grating. By incorporating a transverse Bragg grating into a large-area laser, the optical modes of the laser can be designed to improve the efficiency compared to traditional index-guided lasers. The resulting transverse Bragg resonance (TBR) waveguide can be designed to have a single lateral mode that is distributed throughout the entire width of the laser for efficient, stable, single lateral mode operation even at high powers. In addition, by designing the dispersion of the TBR modes, we can increase the modal gain at the desired lasing frequencies for further efficiency improvements. We have finished some preliminary measurements of our laser samples and are currently working on optimizing the design for improved performance as well as more detailed measurement and characterization. Our initial findings indicate that the

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Semiconductor Based Transverse Bragg Resonance (TBR) Optical Amplifiers and Laser

Grant No: FA9550-05-1-0463

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1. Objectives

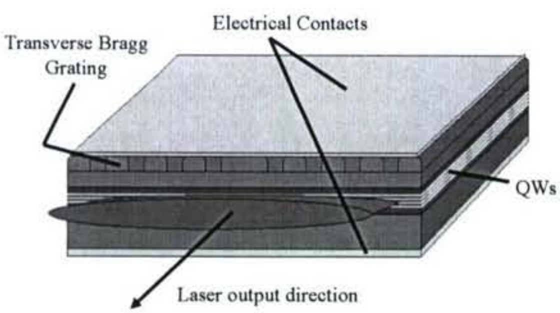
Our objective is to demonstrate and investigate the properties of semiconductor Transverse Bragg Resonance (TBR) optical amplifiers and lasers. (Unchanged)

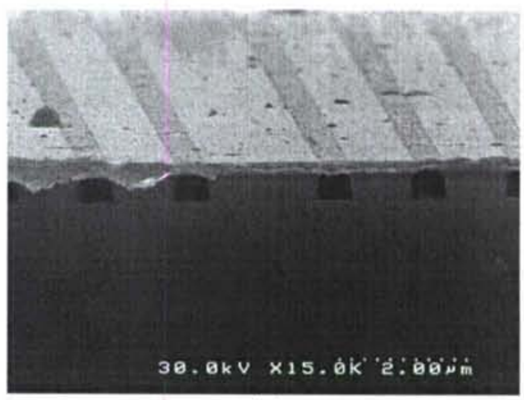
2. Status of effort:

We have fabricated electrically pumped, semiconductor TBR lasers in the InP/InGaAsP material system to demonstrate the efficiency gains possible by the incorporation of a transverse Bragg grating. By incorporating a transverse Bragg grating into a large-area laser, the optical modes of the laser can be designed to improve the efficiency compared to traditional index-guided lasers. The resulting transverse Bragg resonance (TBR) waveguide can be designed to have a single lateral mode that is distributed throughout the entire width of the laser for efficient, stable, single lateral mode operation even at high powers. In addition, by designing the dispersion of the TBR modes, we can increase the modal gain at the desired lasing frequencies for further efficiency improvements. We have finished some preliminary measurements of our laser samples and are currently working on optimizing the design for improved performance as well as more detailed measurement and characterization. Our initial findings indicate that the TBR laser may show efficiency gains compared to traditional broad-area lasers. We also have designed, fabricated and characterized two dimensional TBR lasers. Our measurement results show that we can control the lasing wavelength by changing the photonic crystal lattice constants for large-area, edge-emitting semiconductor lasers.

3. Accomplishments/New Findings:

1. Fabrication process





(a) (b)

Figure 1. (a) Schematic of a TBR laser. (b) SEM image of a InP/InGaAsP TBR laser showing the surface grating with the central defect guiding region and the p-side electrical contact.

A schematic drawing of a TBR laser incorporating a surface grating is shown in Fig. 1a. The TBR laser is fabricated by e-beam lithography on a commercially grown InP epitaxial wafer with 4 InGaAsP quantum wells with a peak luminescence around 1540 nm. The active region is covered by 170 nm of InGaAsP followed by 400 nm of InP that is used to form the surface grating. This is capped with 5 nm of InGaAs. The grating is transferred with a two step wet etch of diluted $HBr:HNO_3$ and HCl acids. A BCB

(Cyclotene 3022-46) planarization layer is applied to bridge the gaps between the grating ridges and etched back with an O_2/NF_3 inductively coupled plasma reactive ion etch (ICP-RIE) followed by thermal evaporation of p-type electrical contacts, AuZn/Au. After mechanical lapping, the n-type contacts, AuGe/Au, are applied and bars are cleaved. A cross section of a finished device is shown in Fig. 1b.

2. Electrically pumped TBR lasing showing preliminary evidence of efficiency gains

The TBR laser was designed to be 100 μm wide with a grating pitch of 1.5 μm. The tested bars were cleaved to a length of 554 μm. The grating pitch was chosen so that the angle of incidence at the facets would be less than the critical angle to prevent total internal reflection. At this grating pitch, all wavelengths within the gain spectrum should be able to couple light out.

The lasers were tested in pulsed mode with no active cooling to minimize heating effects. Pulse settings were 50 ns pulses and a 40 μs period. The light-peak current density curves are shown in Fig. 2. The TBR threshold current density was measured to be 446 A/cm^2 and the broad area threshold current density was measured to be 718 A/cm^2, corresponding to a 38% reduction of the threshold current density. Since the lasers being compared have different lengths, we need to consider the effect of length on threshold current density [1].

The threshold current density can be approximated as:

$$J_{th} \approx qM \exp[2(\alpha_i + \alpha_m)/(\Gamma g_0)] \qquad (1)$$

where q is the electron charge, M is a material parameter describing the internal quantum efficiency and factors affecting the transparency carrier density, α_i the average internal loss , α_m the mirror losses, Γ the confinement factor, and g_0 a normalizing gain constant.

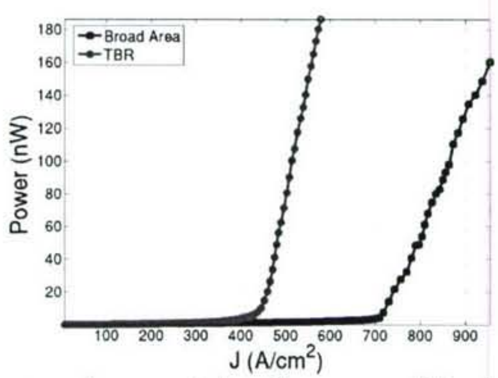


Figure 2. Light vs. peak current density curve of the broad area laser and the TBR laser. The TBR laser has a threshold current density about 38% less while being about 15% shorter and twice as wide.

Since the lasers are fabricated from the same wafer material with the same quantum wells and the same vertical confinement, we assume that M, α_i, Γ, and g_0 are reasonably equivalent. Then, the only term that is dependent on the length is α_m, the mirror losses. For a symmetric device (the 2 facets are the same),

$$\alpha_m = (1/L)\ \ln(1/R) \quad (2)$$

defines the length dependence. As L increase, α_m decreases and reducing the mirror loss term should decrease the threshold current density. In other words, as the length increases, the mirror loss contribution becomes less dominant compared to the internal loss term. Thus, we would expect that a slightly longer device will have a lower threshold. Since the broad area laser is 100 μm longer, cutting it shorter or making the TBR longer would only make the threshold difference larger.

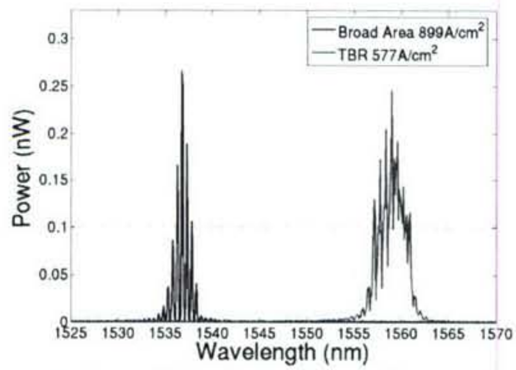


Figure 3. Lasing spectra of the broad area laser and the TBR laser at similar peak output power levels. The TBR laser is red-shifted about 22 nm although it is fabricated from the same wafer material as the broad area laser.

Fig. 3 shows the lasing spectra of the two devices for similar power levels. Since the transverse Bragg grating does not affect the longitudinal modes of the laser, there is no frequency selection beyond the Fabry-Perot resonances due to the facet reflections. The peak lasing wavelength of the broad area laser is approximately 1537 nm while the TBR lases at approximately 1559 nm. This 22 nm red shift of the peak lasing wavelength is also apparent on other TBR devices of the same grating design from the same wafer as compared to other broad area lasers also from the same wafer. Thus we conclude that the spectral shift may be a result of the TBR structure, but possibly due to resistive heating effects rather than the optical mode design. Further evidence of this is seen in the near-field image showing the modal structure (see below).

4. Modal structure

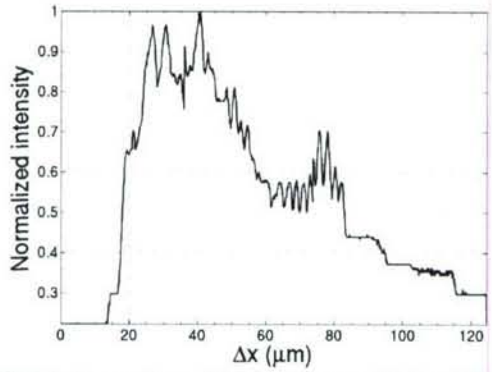


Figure 4. Near field intensity distribution of the TBR laser. The peak intensity on the left corresponds to the electrical contact pad where current is applied through a probe tip.

Fig. 4 shows the near-field intensity distribution as captured with a Vidicon infrared camera. The period of the intensity modulation is approximately 1.8 μm. This roughly corresponds to the grating pitch and provides evidence that the TBR laser is lasing in a high order mode with fast oscillations on the order of the grating pitch. The left of the profile, $\Delta x \sim 0$ μm, corresponds to a contact pad at the edge of the TBR laser where a probe was applied. The intensity gradient, with greatest intensity near the contact pad, suggests there is a large inhomogeneity in the current distribution across the laser indicating the contacts may have poor conductivity.

Our findings thus far show that lasers based on TBR waveguides have the potential for controlling the lateral modes of a large area laser, limiting it to a single transverse mode and increasing efficiency by providing a larger modal gain. An electrically pumped TBR laser based on an InP/InGaAsP material system was demonstrated in pulsed operation. Compared to a gain-guided broad area laser, the TBR laser showed a reduced threshold current density (about 38% less), suggesting that significant efficiency improvements may be possible. However, the contacts may have high resistance leading to heating and poor current distribution. While these features are nonideal, the TBR laser shows promise meriting further investigation for application to high power, high efficiency, large-area lasers.

5. Longitudinal mode control for TBR lasers

A TBR laser has multiple longitudinal modes because the longitudinal feedback mechanism is provided by the Fabry-Perot resonances from the reflection at the end facets. We design a two dimensional Bragg grating (2DBG) structure with two quarter-wave slip line defects to control the optical modes in both longitudinal and transverse directions by incorporating a longitudinal Bragg grating into a TBR waveguide. The resulting 2DBG laser makes single transverse and longitudinal mode operation possible through the proper design of the gratings and defects. Unlike conventional two dimensional photonic crystal lasers, which use a large refractive index perturbation to confine light in a plane, the 2DBG structures described here selectively control longitudinal and transverse wavevector components using a weak index perturbation. Thus, the optical modes confined by the grating in a 2DBG laser will spread out into the periodic active medium, allowing for high power operation.

Figure 5 shows a schematic of a typical structure of a 2DBG laser. The laser consists of a rectangle lattice array of air holes with two line defects in a thin slab, which includes active multiple-quantum-well layers. In the limit of weak index perturbation, which obtains for example for sufficiently small hole diameter, the optical mode for the proposed structure can be separated into transverse (x), vertical (y), and longitudinal (z) components. In the wafer plane (x-z), a mode that satisfies both transverse and longitudinal Bragg resonance conditions will be confined due to the distributed Bragg reflection. Light that does not satisfy the Bragg conditions will be lost. This Bragg condition can be expressed as:

$$k_x = l\frac{\pi}{a}, k_z = j\frac{\pi}{b} \quad (l \neq 0, j \neq 0),$$

where k_x is the transverse wavevector, k_z is the longitudinal wavevector, a is the transverse grating period, b is the longitudinal grating period, and l, j are the orders of the grating. Because the vertical wavevector k_y is determined by the wafer epitaxial layer structure, k_x and k_z satisfy:

$$k_x^2 + k_z^2 = n_{eff}^2 k_0^2,$$

where n_{eff} is the effective refractive index for the optical mode of the wafer structure. In our design, we chose $k_z \approx n_{eff} k_0$. Two line defects perpendicular to each other are introduced in the 2DBG to define the optical resonance condition in the longitudinal and transverse directions. Thus, the widths of two line defects should satisfy [1, 2]:

$$W_1 = (2m+1)a/2l, W_2 = (2n+1)b/2j,$$

Where W_1 is the transverse defect width, W_2 is the longitudinal defect width, and m, n are integers (see Fig. 5).

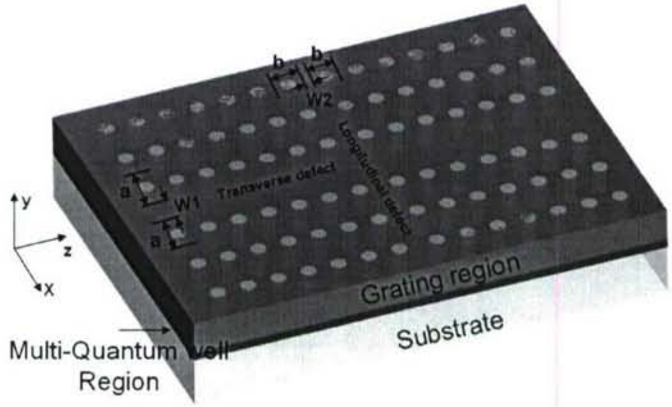
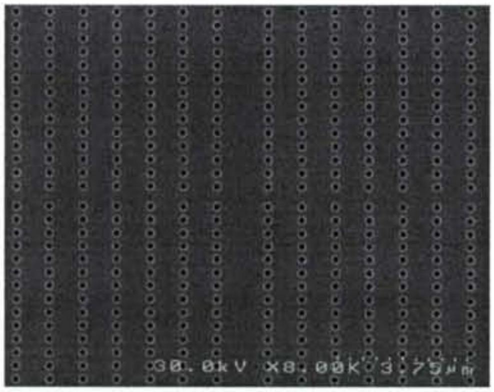


Figure 5. An illustration of a two dimensional Bragg grating laser with two line defects. a is the transverse grating period, b is the longitudinal grating period, W_1 is the transverse defect width, and W_2 is the longitudinal defect width

We are currently working on the fabrication and measurement of those devices. Figure 6 show some SEM pictures of the fabricated devices. The transverse grating provides the wave guiding mechanism and transverse modal control, which enables us to engineer large, distributed modes for high power application. The longitudinal grating provides the longitudinal feedback and modal selection mechanism. Two dimensional grating structure allows a single-transverse and single-longitudinal mode lasing and independent modal control in the transverse and longitudinal direction.



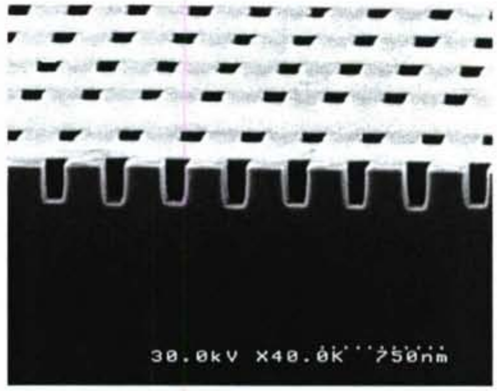


Figure 6. The fabricated two dimensional Bragg grating lasers.

6. Angled facet design for TBR lasers

In TBR structures, modes which are not guided by the transverse grating can also lase when gain is provided. First, effective index-guided mode can exist when the cladding index is smaller than the low index region of the transverse grating. Second, low-loss leaky modes due to incomplete TIR (gain-guided modes) can exist in these wide waveguide structures regardless of the cladding index. Thus, we need a formalism that accounts for all the modes of the structure as well as their losses. For the practical laser design based on the transverse Bragg reflection, we also need to engineer the grating guided modes to be the preferred modes. Here we use a transfer matrix method (TMM) to analyze the modal gain of all the possible modes supported by the TBR waveguide. We also define the modal angle as $\theta = \cos^{-1}(\mathrm{Re}(\beta)/(2\pi n_{avg}/\lambda))$

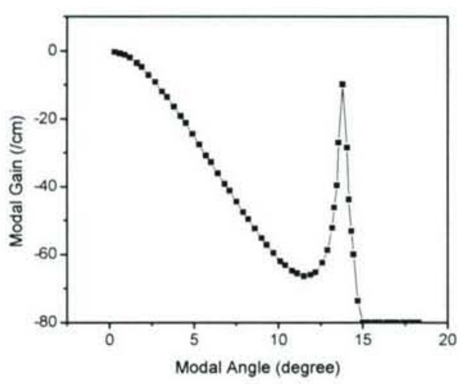


Fig.7 Modal gain vs modal angle for a typical TBR waveguide.

As shown in Fig.7, the modes with small modal angles experience zero or very low radiation loss. We call these modes small modal angle (SMA) modes. SMA modes include both lossless effective index-guided modes and low loss leaky modes. They are almost parallel to the graing and do not radiate significantly. As the modal angle increases, all the modes experience higher radiation loss. However, around the transverse resonance angle of 13.8°, low loss modes exist. These modes are supported by the transverse grating and are therefore the TBR modes. For a finite structure, TBR modes are leaky due to non-unity grating reflectivity. Compared to the SMA modes, TBR modes have much larger intermodal discrimination between the lowest loss and the next lowest loss modes, which is the key in realizing a single transverse mode operation.

To ensure a single transverse mode operation near the Bragg resonance, the feedback mechanism needs to be tailored. Compared to SMA modes, TBR modes have a much "faster" spatial oscillation in the transverse direction. Thus, if we can integrate a spatial filter at the facet to favor the fast spatial oscillation, TBR modes can be preferred. Angled facets were proposed in Ref. [2] to realize this goal. The angled facets act exactly like a spatial filter and feedback from the facet will only be provided for the mode whose modal angle is very close to the tilt angle.

7. Measurement results of two dimensional TBR lasers

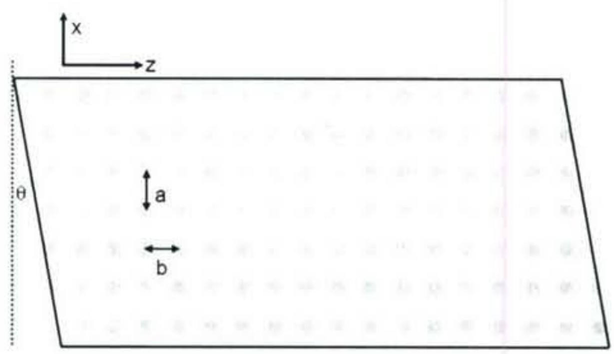


Fig.7 Schematic of fabricated two dimensional TBR lasers.

We first use a first order Bragg reflection (l = 1) for the transverse direction with a lattice constant of a = 1μm and a second order Bragg reflection (j = 2) for the longitudinal direction with three different lattice constants of b = 480nm, 490nm and 500nm. The metal contact width is about 100μm. The tilt angle is 13.8°for all the three designs. The laser bars are cleaved to lengths of about 480μm and are tested in pulsed operation at room temperature with no active cooling. Current pulses with duration of 100 ns and a period of 10 μs are injected to drive the lasers.

Lasing is obtained for the b = 490nm and 500nm designs with different threshold current densities of Jth = 1.10kA/cm2 and 1.33KA/cm2, respectively. Figure 8 shows the optical spectra for all the three designs at the same pump current density J = 1.40kA/cm2. While lasing is not obtained for the device with b = 480nm, the resonance peak at 1523.1nm is evident in the spectrum. The reason that the b = 480nm design does not lase is due to the fact that the resonance peak wavelength for this design is far away from the peak wavelength of the gain spectrum and intrinsic losses at short wavelengths are high. Since the resonance wavelength for the 490nm design is closer to the gain spectrum peak, the threshold for this design is lower.

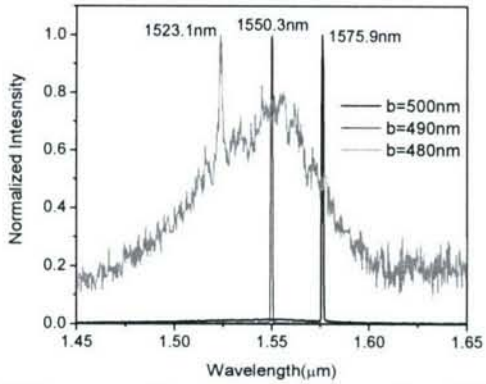


Fig.8 Spectra of tested two dimensional TBR lasers.

In all the three designs, the experimental resonance wavelengths of 1523.1nm, 1550.3nm, and 1575.9nm are close to the theoretical predictions of 1520.2nm, 1550.1nm and 1579.9nm calculated from (1). is chosen to be 3.257 in the calculation and it is numerically calculated by a mode solver for the wavelength of 1550nm. The slight difference at 1523.1nm and 1575.9nm is mainly due to the material dispersion.

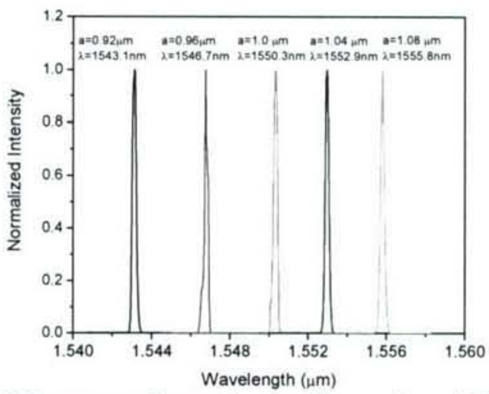


Fig.9 Spectra of tested two dimensional TBR lasers.

We fabricate lasers with the same longitudinal constant of b = 490nm and five different transverse lattice constants of a = 0.92μm, 0.96μm, 1.0μm, 1.04μm, and 1.08μm on the same chip. Other fabrication parameters are the same as the previous examples. Figure 9 shows the lasing spectra at ~1.5× threshold for all the five lasers. As the transverse lattice constant changes from 0.92μm to 1.08μm, the lasing wavelength shifts 12.7nm. This corresponds to a transverse tuning sensitivity of 0.08, thirty times smaller than the longitudinal tuning sensitivity. The small tuning sensitivity is important for accurate control of the lasing wavelength.

References:

[1] L.A. Coldren, and S.W. Corzine, "Diode lasers and photonic integrated circuits," (J. Wiley & Sons, Inc., New York, NY, 1995) pp45-46.

[2] R. J. Lang, K. DZurko, A. Hardy, S. Demars, A. Schoenfelder and D. Welch, "Theory of grating-confined broad-area lasers," IEEE J. Quantum Electron., 34, 2196-2210, 1998.

4. Personnel Supported:

Personnel	Type
Yariv, Amnon	Professorial Faculty
Cooper, Kevin M.	Bi-Weekly Research Staff
Ghaffari, Alireza	Bi-Weekly Research Staff
Choi, John Myun	Grad Assistantship
Lin, Zhu	Grad Assistantship

5. Publications Oct. 2004 - Feb. 2007

[1] L. Zhu, X. K. Sun, G. A. DeRose, A. Scherer, and A. Yariv, Continuous-wave operation of electrically-pumped, single-mode, edge-emitting photonic crystal lasers, Applied Physics Letters 90 (26): 261116, 2007

[2] L. Zhu, P. Chak, J. K. S. Poon, G. A. Derose, A. Yariv, and A. Scherer, Electrically-pumped, broad-area, single-mode photonic crystal lasers, Optics Express 15 (10): 5966-5975, 2007

[3] L. Zhu, G. A. DeRose, A. Scherer, and A. Yariv, Electrically-pumped, edge-emitting photonic crystal lasers with angled facets, Optics Letters 32 (10): 1256-1258, 2007

[4] G. A. DeRose, L. Zhu, J. M. Choi, J. K. S. Poon, A. Yariv, and A. Scherer, Two dimensional Bragg grating lasers defined by Electron Beam Lithography, Journal of Vacuum Science and Technology B 24 (6): 2926-2930, 2006

[5] L. Zhu, J. M. Choi, G. A. DeRose, A. Yariv and A. Scherer, Electrically pumped two dimensional Bragg grating lasers, Optics Letters 31 (12): 1863-1865, 2006.

6. Interactions/Transistions

a. Participation/presentations at meetings, conferences, seminars, etc.:
J.M. Choi, L. Zhu, W.M.J. Green, G. DeRose, and A. Yariv, "Large-area, semiconductor transverse Bragg resonance (TBR) lasers for efficient, high power operation," submitted to ICALEO 2005. (Oct. 30 - Nov. 3)

b. Consultative and advisory functions to other laboratories and agencies: None.

c. Transitions: None.

7. New discoveries, inventions, patent disclosures

US Patent #6,934,425 Issued: 8/23/2005
Transverse Bragg Resonance Lasers and Amplifiers and Method of Operating the Same
Inventors: Yariv, Amnon

Canada Patent Serial #2513214, filed
Transverse Bragg Resonance Lasers and Amplifiers and Method of Operating the Same
Inventors: Yariv, Amnon

Europe Patent Serial #04704931.7, filed
Transverse Bragg Resonance Lasers and Amplifiers and Method of Operating the Same
Inventors: Yariv, Amnon

8. Honors/Awards

Prof. Yariv is a member of the American Physical Society, Phi Beta Kappa, the American Academy of Arts and Sciences, the National Academy of Engineering, the National Academy of Sciences, a Fellow of the Institute of Electrical and Electronics Engineers and the Optical Society of America. He was the recipient of the 1980 Quantum Electronics Award of the IEEE, the 1985 University of Pennsylvania Pender Award, the 1986 Optical Society of America Ives Medal, the 1992 Harvey Prize, the 1998 OSA Beller Medal and received an Honorary Doctorate, December 2000 from Ben Gurion University of the Negev, Isral